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Waveform analysis for high-frequency FMICW radar

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Abstract: The paper describes the waveform analysis for an experimental long-range high-frequency radar system with a design capability for over-the-horizon detection of ocean surface targets up to 400 km from shore with a range resolution of 400 m. Motivated by the need to maximise the transmitter duty cycle in order to detect long-range targets, the radar is based on a frequency modulated interrupted continuous wave (FMICW) type waveform. The interrupt sequence, which is necessary for a high power monostatic operation, complicates the analysis of the radar performance in terms of the ambiguity function (AF). This paper analyses the range dependent AF of FMICW waveforms and proposes practical interrupt sequences for the synthesis of desired AFs.

1 Introduction

The authors are involved in the construction of a shore-based long-range high-frequency (HF) radar facility for iceberg detection, ship tracking and ocean environmental measurements. At these frequencies, electromagnetic waves are capable of over-the-horizon (OTH) propagation in either the ground wave (GW) or sky wave mode. This prototype system relies on the GW mode of propagation and has a design capability for OTH detection and tracking of targets up to 400 km from shore with a range resolution of 400 m [1]. The main objective is to develop techniques for the radar waveform analysis and synthesis to achieve the desired performance specifications for the prototype radar.

In a conventional single-frequency pulsed radar system, the desired range resolution determines the pulse length. Range is computed as the time delay of returned echoes. The maximum range is determined by the repetition rate of the pulses and the hardware limit on the maximum achievable pulse peak power. It is well known (see for example Reference 2) that pulse compression techniques can be used to realise high energy pulses with low peak powers. These waveforms can be compressed, after reception, using simple hardware and/or software operations. For example, using a linear frequency modulated (FM) sweep during the radar pulse, large pulse compression ratios can be achieved. The range measurement of FM radars is based on the difference in instantaneous frequency between the transmitted and received waveforms. The received waveform from a stationary target, with a two-way travel time of t_0 seconds, differs in instantaneous frequency from the received waveform by $(f_0 = \alpha t_0)$, where α is the frequency sweep rate. However, the linear FM pulse waveform has a range/Doppler ambiguity. This ambiguity may be resolved by using a frequency modulated continuous wave (FMCW) sweep; effectively many realisations of linear FM waveforms are present and target velocity may be unambiguously estimated as the rate of change in range [3]. FMCW radars have a range resolution competitive with pulse radars when the same signal bandwidth is used. A survey of numerous papers addressing different aspects of FMCW radars has been presented by Skolnik [4].

The FMCW waveform, with a 100% duty cycle, is ideal for bistatic or low-power monostatic operation. For the high-power monostatic application of our prototype radar, there are two problems with the FMCW approach. First, the necessary isolation between the transmitter and receiver for continuous operation at HF frequencies is very difficult to achieve. Secondly, due to the propagation losses, the signal levels decrease rapidly with distance and the dynamic range of the signals exceeds that of any available receiver hardware.

To overcome both the above mentioned problems the authors have chosen a frequency modulated interrupted continuous wave (FMICW) type waveform [5] for the prototype radar. This is simply an FMCW waveform which is gated on and off with a well defined sequence, typically a pseudorandom sequence. The concept is to transmit for a period of time and, after the transmitter has been turned off, to receive during the quiet period. Thus, compared to an FMCW waveform, both the transmit and receive waveforms are subjected to different interrupt sequences. The introduction of these interrupt sequences complicates the analysis of the radar performance in terms of the well known ambiguity function (AF). For example, it can be easily shown that the effective gating on the received signal varies with the target range and introduces a range dependence on the AF. The form of this AF has been discussed in the literature [6], however, in Section 3, we will use some properties of the AF to simplify the AF analysis of FMICW radar waveforms with arbitrary transmit and receive interrupt sequences.

The inverse problem of determining the parameters of an FMICW waveform to realise a desired AF is more difficult. Some simplification is possible for a GW-HF surveillance radar, where many targets of interest are slow moving and the zero-Doppler ambiguity function is sufficient to evaluate the performance of the waveform. This zero-Doppler ambiguity function can be easily obtained from the general form of the AF and offers us

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an insight into the effect of different interrupt sequences on the FMICW waveform.

Both random and deterministic interrupt sequences are considered in Section 4. It is shown that random interrupt sequences result in an AF with a high noise floor, which can obscure weaker targets, whereas deterministic sequences cause ambiguity pop-ups. Section 5 details how these ambiguity pop-ups may be successfully controlled, resulting in an AF with a very low noise floor, a signal dynamic range with the capability of available receivers, and a reasonable signal-to-noise ratio (SNR) with respect to FMCW.

2 Background

Modern radar technolgy relies on the AF to evaluate the performance characteristics, such as range and Doppler resolution, of waveforms for different applications [2]. For a radar waveform $\mu(t)$, the AF is generally defined in terms of the response function $\chi(\tau, \phi)$:

$$\mathrm{AF} = \chi(\tau, \phi)\chi^*(\tau, \phi) \tag{1}$$

where

$$\chi(\tau, \phi) = \int_{-\infty}^{\infty} \mu\left(t + \frac{\tau}{2}\right)\mu^*\left(t - \frac{\tau}{2}\right)e^{-j2\pi\phi t}\, dt$$

The response function has two parameters, time delay τ and Doppler frequency ϕ, and can be interpreted as a measure of the correlation of the waveform $\mu(t)$ with a delayed and/or Doppler shifted version of itself. This is used to evaluate the capability of a radar waveform to resolve targets close to each other in range and/or Doppler. For example, the well known 'chirp' waveform is expressed as

$$g(t) = Ke^{j(\alpha t^2)/2} \quad \text{all } t \tag{2}$$

where K is a scaling constant and α is the frequency sweep rate. This ideal 'chirp' waveform is an infinite linear frequency modulated sweep and its response function can be easily evaluated using eqn. 1:

$$\chi_g(\tau, \phi) = |K|^2 2\pi\delta(\phi - \alpha\tau) \tag{3}$$

The response function in eqn. 3, clearly shows the well known range/Doppler ambiguity of the 'chirp' waveform. The characteristics of the response function for more complicated radar waveforms are not so obvious. In particular, the evaluation of the response function for FMICW waveforms is complicated by the finite extent of the linear frequency sweep as well as the effect of the interrupt sequence used. Poole [2] has studied the 'absolute delay-dependent cross-ambiguity function' for FMICW waveforms with pseudorandom interrupt sequences; an important result reported is that the AF is not independent of target range. In the next Section, we present an analysis of the AF of FMICW waveforms in a manner which will allow the subsequent synthesis of desired performance characteristics by using different interrupt sequences.

3 Ambiguity function for FMICW waveforms

The practical implementation of the 'chirp' waveform sets a finite limit on the frequency sweep; a periodic repetition of this finite sweep is known as the FMCW waveform. In the HF band, for a high-power monostatic operation, the transmitter and receiver cannot be effectively isolated for the 100% duty cycle of the FMCW waveform. Thus some form of interruption is required on transmission (FMICW waveform) so that the receiver may be activated during the intervals between transmissions. Our objective here is to evaluate the AF for an FMICW waveform. The different gating sequences imposed on the transmitted and received signals complicates the analysis and also introduces a range dependence of the AF. We will use the properties of the AF to simplify the analysis of some physically realisable FMICW waveforms.

It is important to note that the receiver must always be off whenever the transmitter is on, so that the transmitter and receiver interrupt sequences are not identical. Further differences between the two sequences are introduced by the 'soft gating' used to suppress transients which would be caused if the interrupt sequences were switched rapidly between the on and off states. Depending on the target range, the transmitted waveform is not received in its entirety at the receiver and the radar performance needs to be evaluated by the 'cross response function' between the transmitted and received signals.

The effect of target range on the received signal is demonstrated in Fig. 1 where, for the same transmitted signal, the received signals are shown for two different target ranges. Although the returned signals are similar, the relative time delays in the receiver gating sequences significantly change the actual signals gated into the receiver. The AF will obviously be different for these two ranges and this effect must be carefully considered when designing waveforms for long-range applications.

3.1 Evaluation of the response function components

We will now evaluate the AF for a general FMICW waveform. The soft gating mentioned above is not considered; the low pass filtering effect due to this gating can be easily added at any stage of the analysis. It is possible to write an expression for the AF based on the strict definition [2] but that approach gives little indication of the effect of changing the FMICW parameters on the AF. The derivation presented here evaluates the AF in terms of a number of component response functions which are combined using linear operations. Specifically, only the 'cross response' function for the interrupt sequence needs to be computed. The rest of the derivation involves linear operations and the well known response function of an FM sweep. For example, a single period of an FMCW waveform can be described as the time-domain product of an ideal FM sweep or 'chirp' waveform $g(t)$ and a gate function with width corresponding to the FMCW sweep period T_R. The full FMCW waveform can then be realised by convolving this single period with an impulse sequence having a constant period T_R. The transmitted and received FMICW waveforms are obtained by multiplying the FMCW waveform with the transmit and receive interrupt sequence, respectively.

The interrupt sequence corresponding to the transmitted waveform is defined by

$$0 \leqslant A_T(t) \leqslant 1 \quad -\infty < t < \infty \tag{4}$$

Similarly, the interrupt sequence corresponding to the received waveform is defined by

$$0 \leqslant A_R(t) \leqslant 1 \quad -\infty < t < \infty \tag{5}$$

A fundamental aspect of FMICW operation constrains the receiver to be disconnected whenever the transmitter is operating i.e.

$$A_R(t) = 0 \quad \text{if } A_T(t) \neq 0 \tag{6}$$

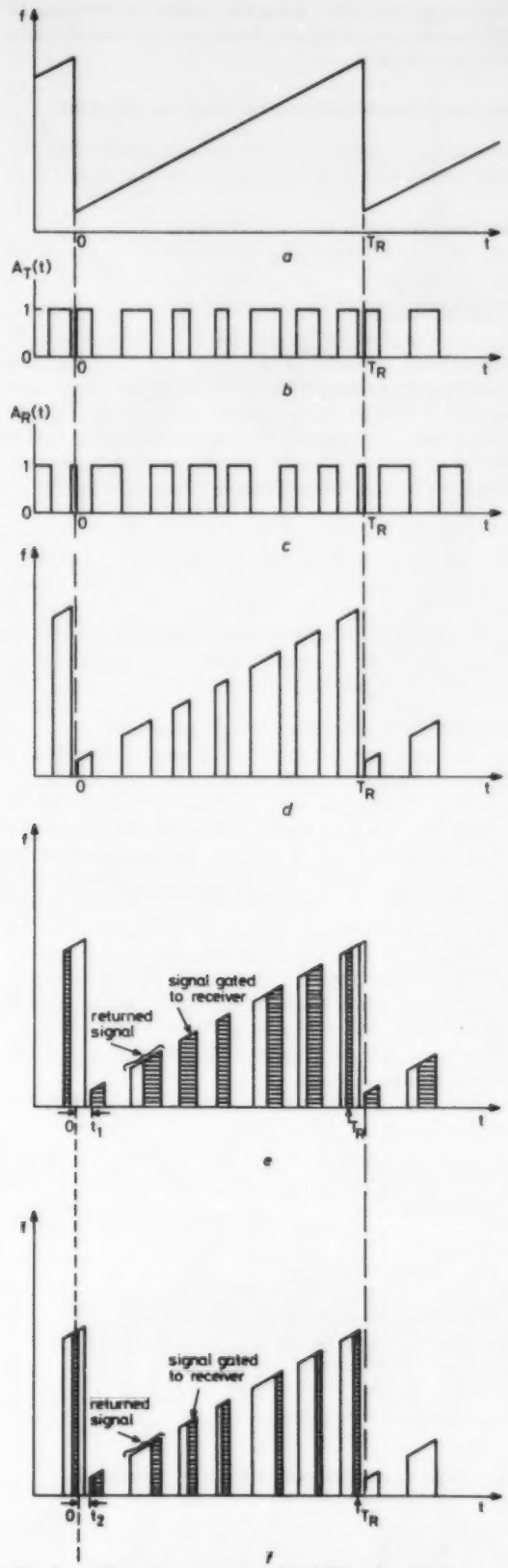


Fig. 1 *Effect of target range on FMICW radar signal*

a Generated FMCW signal
b Transmitter gating sequence
c Receiver gating sequence (complement of transmit sequence)
d FMICW signal using the gating sequence of *b*
e FMICW radar echo from target with two-way travel time of t_1 seconds
f FMICW radar echo from target with two-way travel time of t_2 seconds

It is well known that the response function of the product of two time-domain signals can be evaluated by convolving their individual response functions along the Doppler variable. Thus the ideal response function of the 'chirp' waveform in eqn. 3 is broadened by convolution with the response function of an ideal gate to achieve the response function of a finite FM sweep pulse. The response function of an ideal gate is shown in Fig. 2. From the finite gate $G(t)$ of Fig. 2*a*, the kernel of eqn. 1 is formed as a two dimensional function in t and τ. The response function is obtained by computing the Fourier transform in (t) as per eqn. 1. Note that this linear broadening of the ideal response of the chirp signal may be implemented later to retain simplicity in our derivation. The same comment applies to the operation of convolution with an impulse sequence to form the repetitive sweeps of the FMCW waveform.

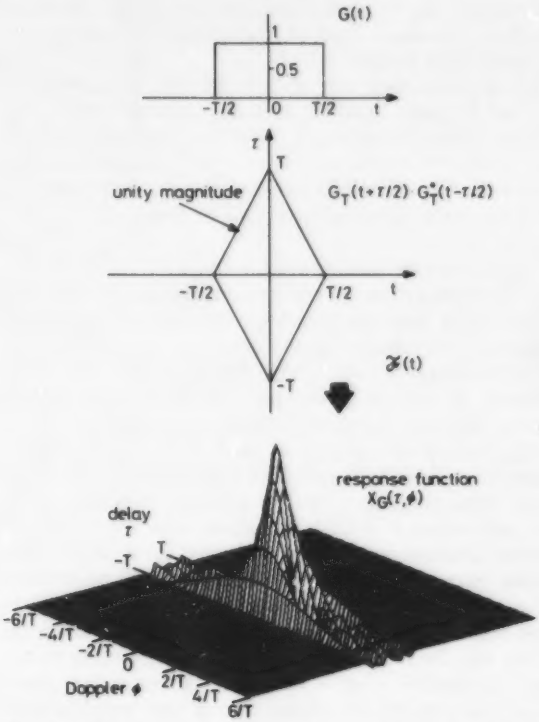


Fig. 2 *Evaluation of the response function corresponding to an ideal gate function using eqn. 1*

Thus, expressing the transmitted waveform as a gated version of an ideal 'chirp' waveform

$$f_T(t) = A_T(t)g(t) \tag{7}$$

The radar returns from targets are delayed by the two-way travel time t_0 and are further modified by the receiver gating sequence

$$f_R(t) = A_R(t)A_T(t - t_0)g(t - t_0) \tag{8}$$

Eqn. 8 may be simply rewritten as

$$f_R(t + t_0) = A_R(t + t_0)A_T(t)g(t) \tag{9}$$

Examination of eqns. 7 and 9 shows that the response function for the FMICW waveform can be evaluated by

(*a*) Evaluating the response function for $g(t)$.

(*b*) Evaluating the 'cross response' function for $A_T(t)$ and $A_R(t + t_0)A_T(t)$.

(*c*) Convolving the above two response functions along the Doppler variable.

(*d*) Convolving the response function of the infinite sequences, with the impulse response of the finite bandwidth.

(*e*) The response function is periodically repeated, in the delay variable, due to the periodic nature of the FMICW sweep.

The response function of the 'chirp' waveform is given by eqn. 3 and contains the effects of any Doppler shift due to target velocity. The 'cross response' function for the transmitter and receiver gating sequences can be easily evaluated using:

$$\chi_f(\tau, \phi, t_0) = \int_{-\infty}^{\infty} A_T\left(t + \frac{\tau}{2}\right) A_R\left(t + t_0 - \frac{\tau}{2}\right) \times A_T\left(t - \frac{\tau}{2}\right) e^{-j2\pi\phi t}\, dt \quad (10)$$

Note that this two-dimensional response function depends on the delay time, i.e. the ambiguity function will vary with target range.

The response function of eqn. 10 can be convolved, along the Doppler variable, with the response function of the ideal 'chirp' waveform to give the response function of the FMICW waveform. This ideal response function can now be broadened to account for the soft gating as well as the finite bandwidth of the FM sweep.

3.2 Zero Doppler ambiguity function

In many applications of HF radars, the target velocities are very small and the zero-Doppler ambiguity function is sufficient to evaluate the performance of the waveform. This zero-Doppler ambiguity function can be easily evaluated. It can be seen that the convolution of the response function of eqn. 10 with the response function of the ideal chirp of eqn. 3, at each value of the delay parameter, will shift the response function (eqn. 10) in frequency. This frequency shift is a linear function of the delay parameter τ. A little reflection will show that the response function needs to be evaluated for a set of delay-Doppler parameters such that the values will be mapped to the zero Doppler axis after convolution with the simple response function (eqn. 6) of the 'chirp' waveform. For this set, the Doppler frequency corresponding to any delay τ is simply $-\alpha\tau$, where α is the frequency sweep rate of the 'chirp' waveform. Thus the zero-Doppler response function for an FMICW waveform can be computed using

$$\chi_f(\tau, \alpha, t_0) = \int_{-\infty}^{\infty} A_T\left(t + \frac{\tau}{2}\right) A_R\left(t + t_0 - \frac{\tau}{2}\right) \times A_T\left(t - \frac{\tau}{2}\right) e^{j2\pi\alpha\tau t}\, dt \quad (11)$$

As the mapping to the zero doppler axis depends on the frequency sweep rate, α now appears as a parameter in the evaluation of the response function. From a computational point of view, eqn. 11 may be simplified by replacing t with $(t + \tau/2)$

$$\chi_f(\tau, \alpha, t_0) = \int_{-\infty}^{\infty} A_T(t + \tau) A_R(t + t_0) A_T(t) \times e^{j2\pi\alpha\tau(t + \tau/2)}\, dt \quad (12)$$

Eqn. 12 may be interpreted as the correlation of two sequences $P(t, t_0)$ and $Q(t, \tau)$ given by

$$P(t, t_0) = A_R(t + t_0) A\tau(t)$$
$$Q(t, \tau) = A_T(t + \tau) e^{j2\pi\alpha\tau(t + \tau/2)} \quad (13)$$

The following Section presents some examples of FMICW waveform ambiguity functions evaluated using the above technique.

4 Numerical evaluation of ambiguity function

The two examples presented here are evaluated using the following specifications of the prototype HF long-range radar:

sweep bandwidth, B	375 kHz
sweep repetition period, T_R	0.524288 s
range resolution	400 m
unambiguous range	409.6 km

For the computer simulations the 0.524288 s FMICW sweep repetition period was quantised to 8192 samples corresponding to a sample interval of 64 μs. Note also that the AF is plotted as a function of range in contrast to the usual delay parameter. The main reason for this is that the AF of FMICW waveforms varies with range; the sample delay of 64 μs corresponds to a range of 9.6 km.

4.1 FMCW

FMCW may be thought of as a special case of FMICW, where $A_T(t) = A_R(t) = 1$. However, it varies from FMICW in that $A_R(t) \neq 0$, when $A_T(t) \neq 0$. This case is useful as a benchmark with which to compare FMICW waveforms. In Fig. 3, it is shown that the design resolution of 400 m has been obtained.

4.2 FMICW with random interrupt sequence

Random gating sequences are conventionally chosen as a means to distribute the sidelobe energy of the ambiguity function. Fig. 4*a* shows the interrupt sequence for a simple random gating sequence. The durations T of the periods within the sequence have a normal distribution, as shown in Fig. 4*b*. This distribution was chosen as it can be shown that, for this case, the ratio of the receive power to the transmitted power is constant over all target ranges. This minimises periodicities and produces a near white noise floor of the ambiguity function as shown in Fig. 4*c*. Note that the ambiguity noise floor is only about 30 dB below the target level. This will seriously limit the radar performance for weak targets in the presence of stronger targets.

For ground wave HF radar, the radar range equation [4] is defined as:

$$P_R = \frac{P_T G_T G_R \sigma \lambda^2 W_r^4}{(4\pi)^3 R^4} \quad (14)$$

where

P_T = transmit power
P_R = receive power
G_T = transmit antenna gain
G_R = receive antenna gain
σ = radar cross-section
λ = wave length
W_r = attenuation function
R = range

Thus, the ratio of receive power from two ranges is

$$\frac{P_{R1}}{P_{R2}} = \left(\frac{W_1}{R_1}\frac{R_2}{W_2}\right)^4 \quad (15)$$

and for a transmit frequency of 6.75 MHz, the variation in single strength from 50 km to 400 km is

$$\left(\frac{0.7882}{50} \times \frac{400}{0.0603}\right)^4 = 80 \text{ dB}$$

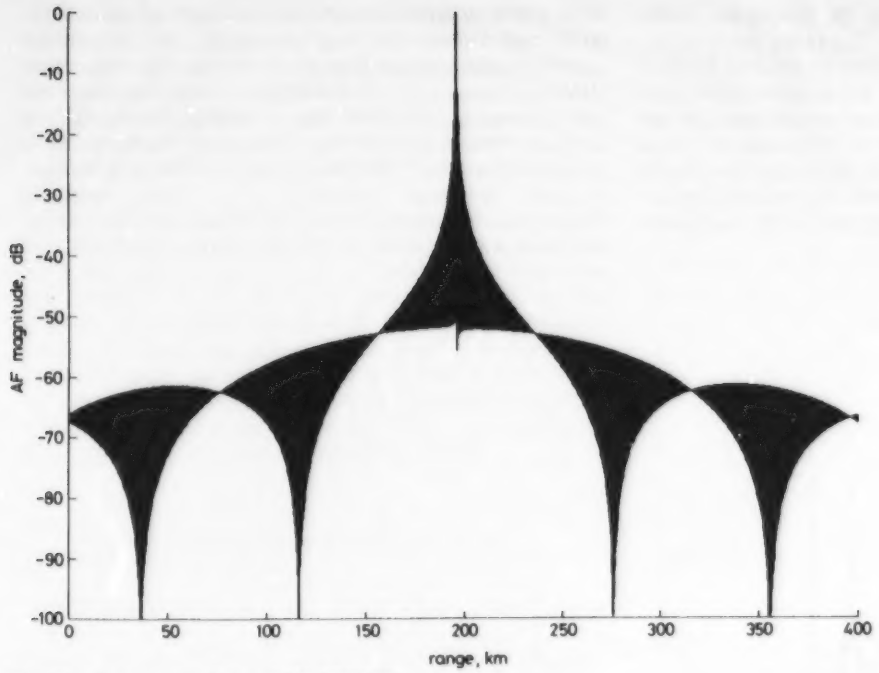
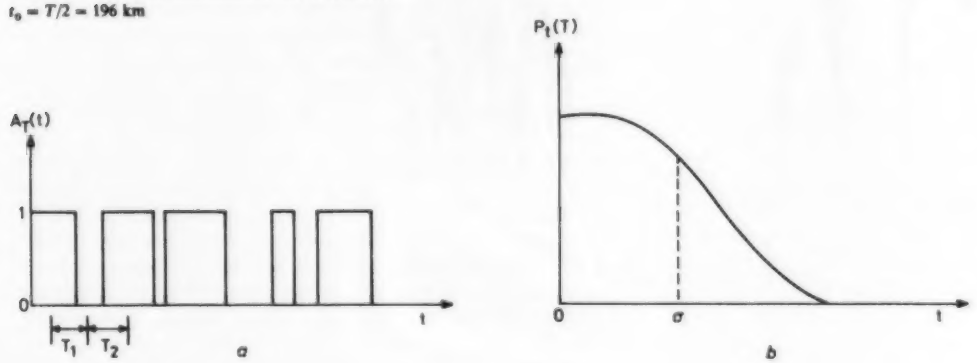


Fig. 3 *Computer simulation of AF of FMCW*
$r_0 = T/2 = 196$ km



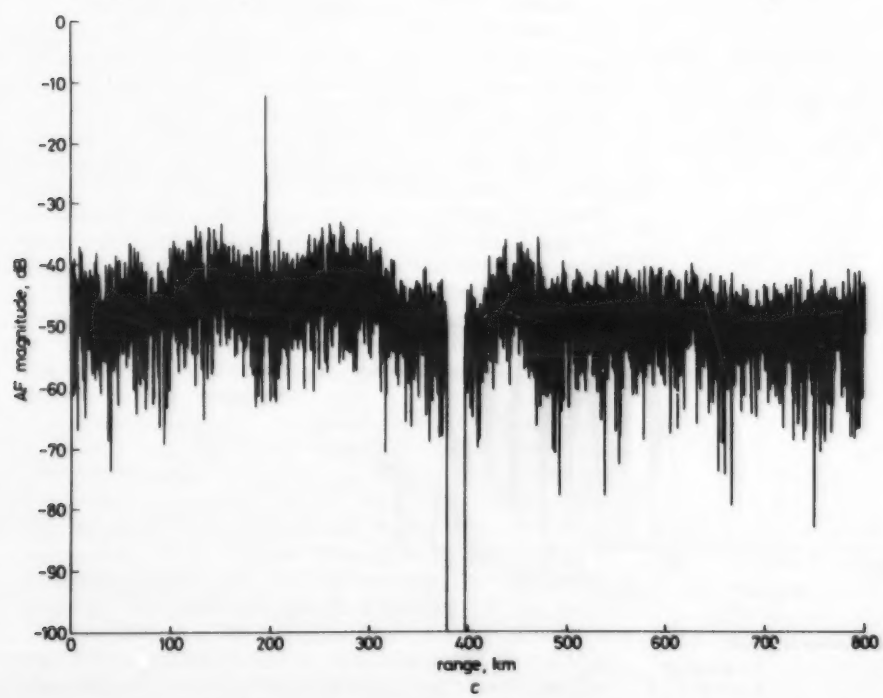


Fig. 4 *AF of FMICW with random interrupt sequence*
a Transmit interrupt sequence
b Distribution of interrupt periods T with variance σ^2
c AF corresponding to interrupt sequence in *a*

After acceptable processing gains the ambiguity noise floor must also roll off by at least the radar range equation, otherwise far signals will always be masked by near signals. For the example of Fig. 4*c*, with an ambiguity noise floor of −30 dB, a near target would mask a far target by up to 50 dB. Suppression of the ambiguity noise floor can obviously be achieved by increasing the length of the interrupt sequence. However, for many applications, the required sequence length cannot be practically realised.

4.3 FMICW with deterministic interrupt sequence

It is well known that any periodicity in the interrupt sequence will produce pop-ups in the ambiguity function. However, these pop-ups are at well defined locations and the ambiguity function has a negligible noise floor between these locations. Fig. 5 shows the ambiguity function produced by FMICW waveforms with simple deterministic interrupt sequences. For these interrupt sequences, the transmitter on time is equal to the receiver on time, and is equal to 196 km. Two targets are con-

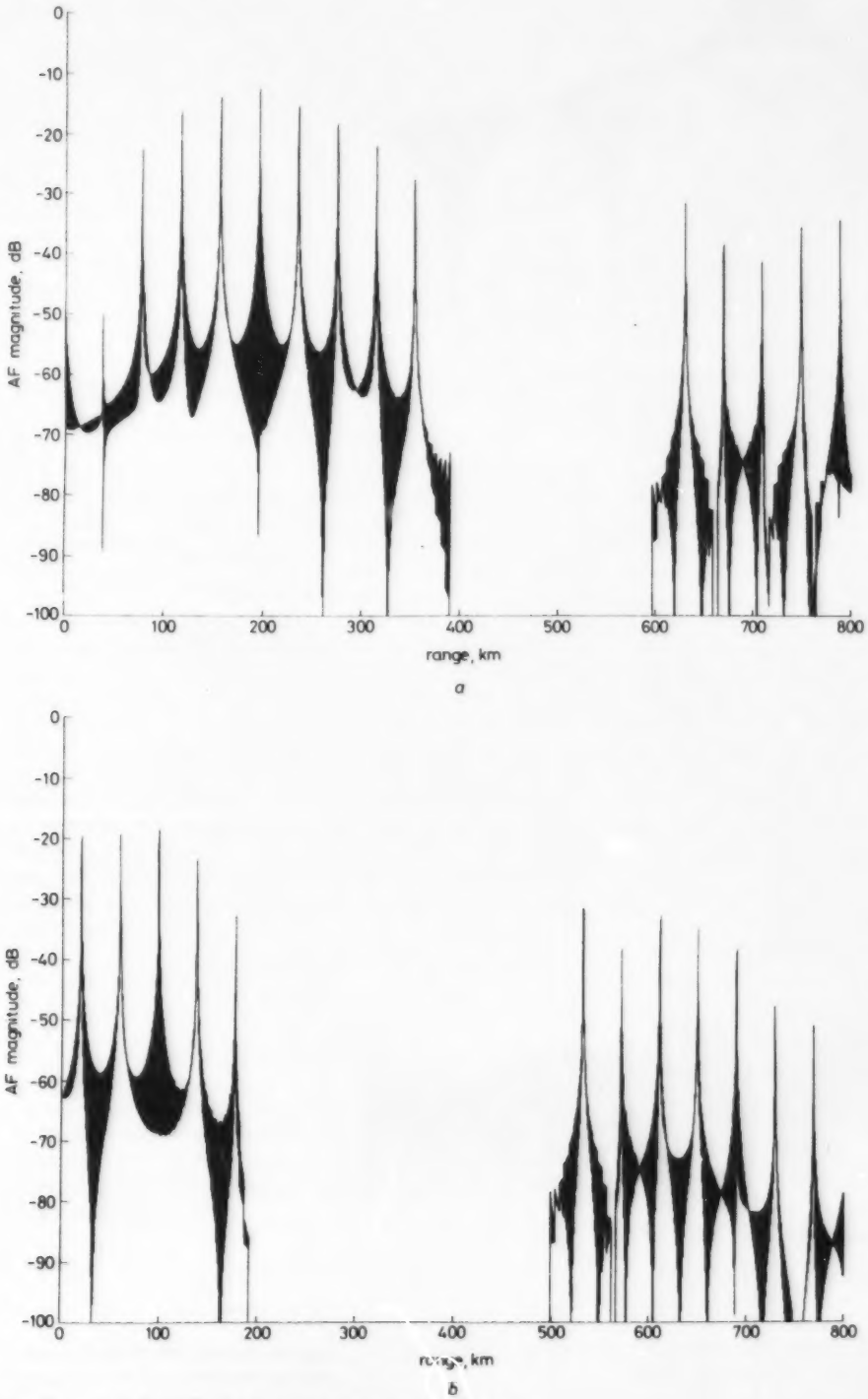


Fig. 5 *AF of FMICW with deterministic interrupt sequence*
a $t_0 = T/2 = 196$ km
b $t_0 = T/4 = 98$ km

sidered, one at 196 km and one at 98 km. Some important features of the AFs of Fig. 5 are clearly evident. The maximum value of the AF varies with the target distance, ambiguity pop-ups are produced and the AF exhibits negligible magnitude between these ambiguity pop-ups. Fig. 5*b* is of interest in that there is a substantial zero magnitude region where there are missing ambiguity pop-ups.

The form of the AF of Fig. 5 suggests that a deterministic interrupt sequence for FMICW may be very useful for some applications. We need to analytically determine the locations of the ambiguity pop-ups as well as the regions of negligible magnitude so that deterministic sequences could be designed for specific applications. Section 5 deals with the analysis of FMICW with deterministic interrupt sequences and an example is presented which implements a waveform with no ambiguity pop-ups within a desired unambiguous range.

5 Analysis of FMICW with deterministic interrupt sequence

As detailed in Section 3, one of the steps in determining the AF of FMICW waveforms is the evaluation of the 'cross response' function between the interrupt sequence and its delayed replica. Changing the interrupt sequence of FMICW only affects this 'cross response' function; consequently this step is treated here in more detail with a view to understanding the locations of the ambiguity pop-ups and the regions of negligible magnitude in the AF. The motivation for this is to investigate the possibility of designing FMICW waveforms with deterministic interrupt sequences without any ambiguity pop-ups within a specified region of interest.

Eqn. 10 shows that the 'cross response' function for the gating sequence is evaluated by a one-dimensional Fourier transform of a two-dimensional function. For a simple example of a deterministic interrupt sequence, Fig. 6*a* shows how the transmitted and received waveforms are gated. It is instructive to plot the above mentioned two-dimensional function for these sequences as shown in Fig. 6*b*. This is referred to here as a 'diamond plot'. The magnitude of the areas within the diamonds is unity, and that outside is zero. The 'cross response' function in Fig. 6*c* is obtained, as indicated by eqn. 10, by the Fourier transform of Fig. 6*b* along the 't' variable. Note that the function in Fig. 6*b* is strictly periodic, with period T, along the 't' variable and also that this function extends to infinity. Thus, the 'cross response' function has a discrete spectrum and can be easily evaluated knowing the Fourier transform of a periodic gate. The lines in Fig. 6*c* represent the locations of the discrete spectral lines. Fig. 7 shows how the magnitude of these spectral lines varies as a function of delay or Doppler. The above theory is linear, and the final results may be obtained by convolving with a finite bandwidth.

As described earlier, the zero-Doppler AF is obtained by convolving the 'cross response' function with the response function of the FM sweep. This is indicated by the zero-Doppler mapping line on Fig. 6*c* which selects the values of the 'cross response' function which will be mapped to zero Doppler after convolution with the response function of the FM sweep. The ambiguity pop-ups will occur at the intersections of the zero-Doppler mapping line with the discrete spectral lines of the 'cross response' function. It can be easily shown that the ambiguity pop-up period is independent of target distance and is given by

$$T_a = 1/(\alpha T) \tag{16}$$

where T is the period of the interrupt sequence and α is the FM sweep rate.

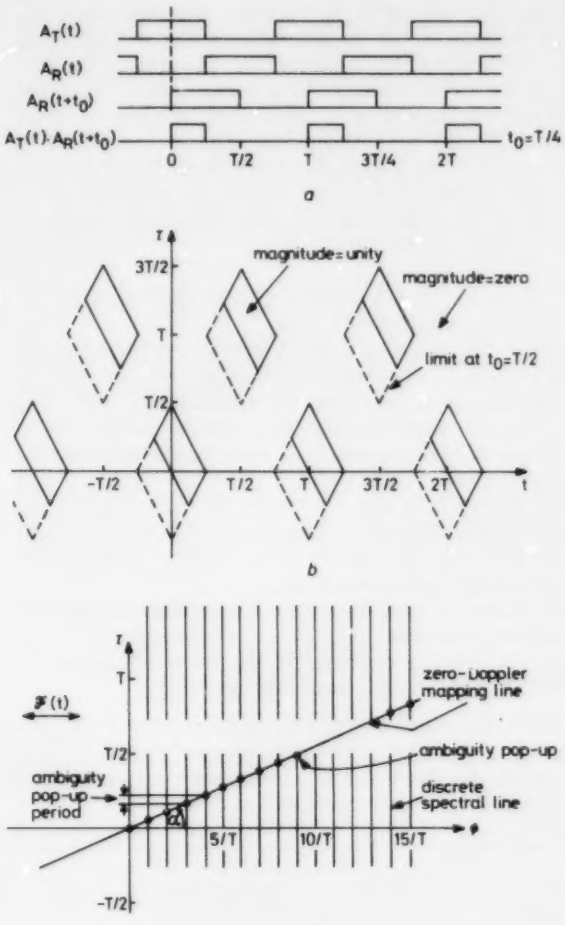


Fig. 6 *Response function of interrupt sequence*
$t_0 = T/4$
a Deterministic interrupt sequence
b $A_T(t+\tau/2)\,A_R(t+t_0-\tau/2)\,A_T(t-\tau/2)$
c Fourier transform of *b* along the t variable

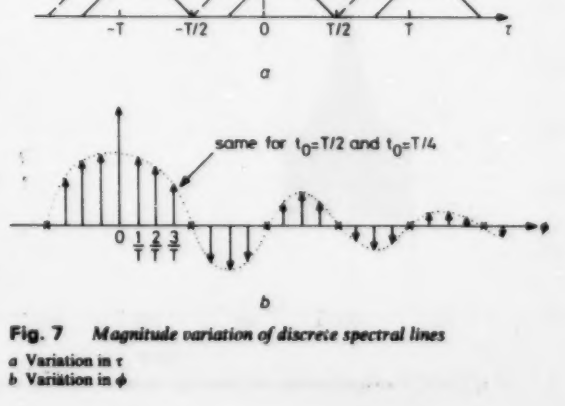


Fig. 7 *Magnitude variation of discrete spectral lines*
a Variation in τ
b Variation in ϕ

Eqn. 16 can be used to check the ambiguity pop-up period for the example in Section 4. The computed period of 40.96 km agrees with the plotted results in Fig. 5.

An interesting effect occurs when, for the interrupt sequence described above, the target distance is less than half the gate period ($T/2$). Consider the case when the target distance is $T/4$, as illustrated in Fig. 8. This figure is very similar to Fig. 6 except that the area of the diamonds has been reduced. As a consequence, the 'cross response' function is zero over some regions of delay which will map zero magnitude regions into the zero-Doppler AF. This feature will allow us to design a deterministic sequence with no ambiguity pop-ups in a selected set of ranges and with zero magnitude regions in the zero-Doppler AF.

5.1 *Design example of FMICW with deterministic interrupt sequence*

Consider the transmit and receive interrupt sequences shown in Fig. 8. For these sequences, the receiver on time is significantly larger than the transmit on time. The diamond plot shown in Fig. 8*b* is somewhat modified if the target distance approaches the extreme near and far ranges. However, this does not affect the repetition rate of the diamonds in the 't' variable, and the zero magnitude response function in the range ($T_1 < t_0 < T_2$) is unchanged. Fig. 8*b* clearly shows that a large unambiguous range may be achieved by:

(*a*) Ensuring that there are no ambiguity pop-ups within the diamonds.

(*b*) The repetition period of the diamond pattern is greater than the desired unambiguous range.

Both of these conditions can be easily satisfied. Comparison of eqn. 16 and Fig. 8*b* shows that ambiguity pop-ups within the diamonds can be eliminated by ensuring that the transmit on time is less than $1/(\alpha T)$:

$$T_1 < 1/(\alpha T) \tag{17}$$

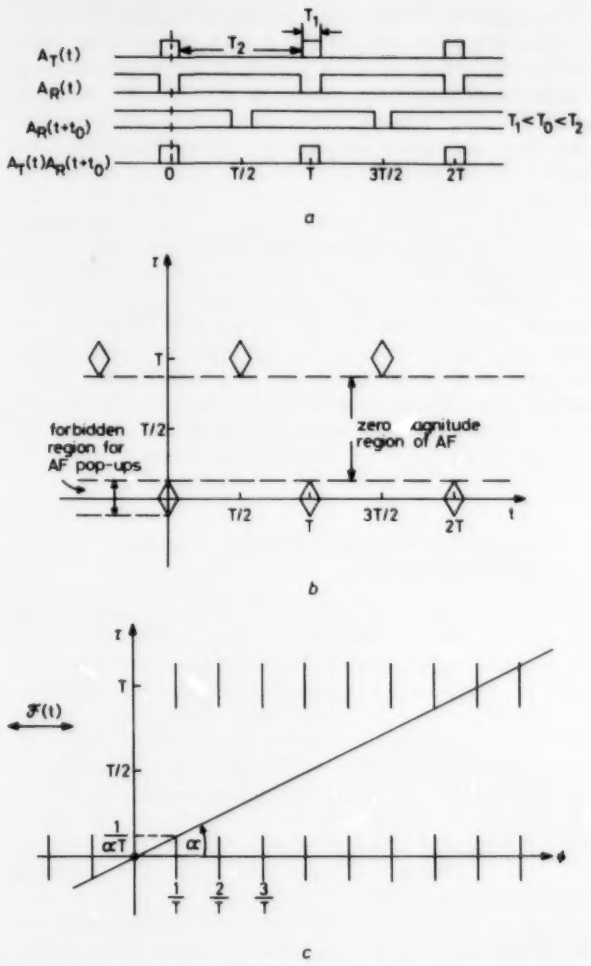


Fig. 8 *Response function, similar to Fig. 6, of interrupt sequence with low duty cycle*

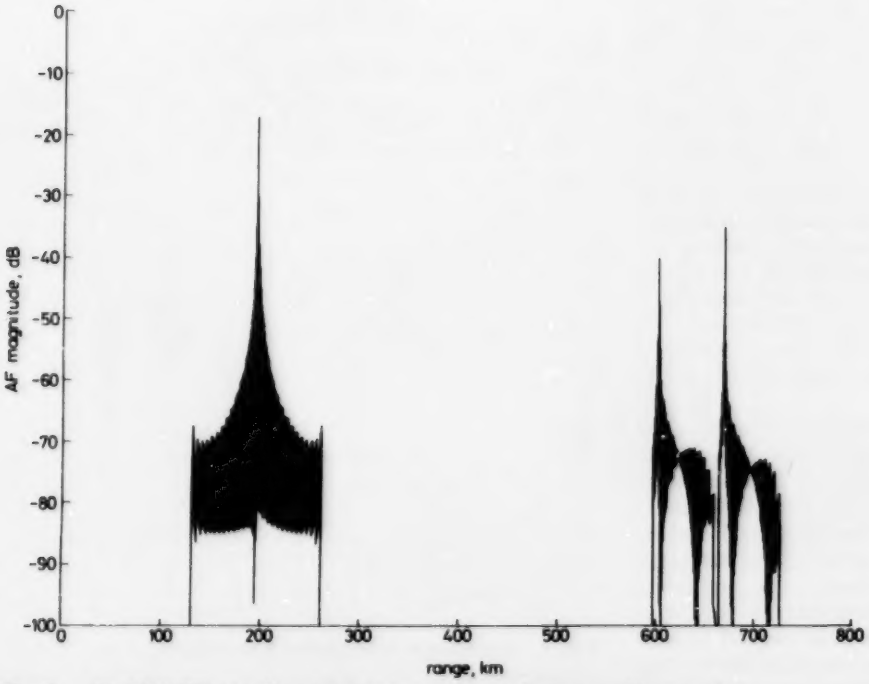


Fig. 9 *AF of FMICW using deterministic interrupt sequence showing unambiguous region*

The pulse repetition period is obviously determined by the unambiguous range and thus the penalty for ensuring eqn. 17 is a decrease in duty cycle of the transmitter.

The following example details the practical design of an FMICW waveform for the prototype HF radar using the specifications listed in Section 4. The pulse repetition rate was chosen to correspond to 467 km. The transmitter on time, corresponding to 67 km, was then determined using eqns. 16 and 17. The results of a computer simulation are shown in Fig. 9. There is only a single pulse at the target location and all other ambiguity pop-ups have been suppressed. The extremely low noise floor of the ambiguity function will allow targets, well separated in signal powers, to be easily detected.

5.2 Signal to atmospheric-noise ratio

It has been shown in Fig. 9 that a deterministic sequence can be designed with no ambiguity pop-ups over a desired unambiguous range. The cost is a reduced signal-to-noise ratio (SNR) due to a reduced signal against noise length. For the example considered above, the signal length is reduced 8.4 dB from ideal FMCW. As the noise length for any one range is also reduced by 8.4 dB, the SNR reduction from FMCW is only 4.2 dB.

For the normal distribution random sequence considered earlier, the signal length would be reduced to 6 dB (half the signal transmitted, half the transmitted signal actually received). The noise length for any one range would be reduced 3 dB (receiver on half the time). Thus, the SNR reduction from FMCW would be 4.5 dB. A pulse radar, to provide the required resolution of 400 m, with a maximum unambiguous range of 400 km, would have a signal length reduced 30 dB from ideal FMCW. The noise length for any one range would also be reduced 30 dB from FMCW.

A deterministic gating sequence with a duty cycle of -8.4 dB, provides an equivalent SNR to a random sequence with a duty cycle of -3 dB, and it is now possible to temporally isolate the signal for any one target from much of the noise. For a random sequence, the signal is contained over all the receive time, and this temporal filtering is not possible. Also, for targets which are of a distance greater than the width of the transmit pulse, there is a 100% correlation between signal available and receiver on. For a normal distribution random sequence this was 50% for all targets.

6 Conclusion

Analysis and design procedures have been developed for FMICW waveforms to be used in a prototype long-range ocean-surveillance radar. Random interrupt sequences, as typically used in FMICW systems, result in a substantial noise floor of the ambiguity function. However, simulations have shown that FMICW may be employed for HF OTH radar with a deterministic interrupt sequence. The specified resolution and unambiguous range for the prototype radar can be achieved with a 4.2 dB SNR loss compared to an ideal FMCW system. Also, the required dynamic range of the receivers is now limited to a range equal to the width of the transmitter pulse, as is the case for pulse radar. This FMICW waveforms will be implemented shortly in hardware and the performance results reported accordingly.

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